RESULTS OF RECENT RESEARCHES IN COSMICAL EVOLUTION.

(Plate XXXI.)

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Early in 1908 the writer was able to conclude the researches on earthquakes, mountain formation, and kindred phenomena connected with the physics of the earth, which this society did him the honor to publish in four memoirs,[1] and it then became possible to resume the study of the problems of cosmogony, which have been before him uninterruptedly since 1884. For a long time these problems have defied the powers of the mathematician and natural philosopher, yet for the last thirty years enough progress seemed always to be in sight to stimulate the hope and energy of investigators; and many papers have appeared on the subject, especially from Professor Sir G. H. Darwin, while lesser contributions have been made by Lord Kelvin, Newcomb and Poincaré, and others.

The problem of the heat of the sun, due to condensation under gravitation, had been successfully attacked by Helmholtz as early as 1854, and subsequently much improved by the researches of Lane, Lord Kelvin, Ritter and the writer;[2] but the discoveries in molecular physics made during the past decade have shown that the conclusions based on the theory of gravitation alone have to be modified to take account of the energy of molecular transformation made familiar in radio-activity. By this hitherto unsuspected reservoir of natural forces the maintainance of the activity of the sun and stars is greatly prolonged. Accordingly, instead of reckoning the life of the solar system in twenties of millions of years, as estimated by Helmholtz, it is now known that the actual duration

[1] Cf. Proceedings, 1906–1908.

[2] Cf. *A. N.*, 4053.

of our system is to be estimated only in billions of years. This prolongation of the period allowed for the activity of the sun is confirmed by other investigations made by the writer during the past two years, showing that the mode of formation of our system has been excessively slow and very different from what has been generally supposed; and that the principal agency which has operated in its development and in shaping the orbits has been the action of a resisting medium extending over immense periods of time.

I shall not attempt to treat fully of this large subject in the present communication, because it is to be discussed in considerable detail in the second volume of my "Researches on the Evolution of the Stellar Systems," which is now in press and expected to appear during the coming summer or autumn. But it may be useful to give a brief review of the subject to see where we stand, and to sum up what appears to be established by the investigations which have so fully absorbed my energies during the past two years. The present discussion must therefore consist mainly of a summary, and such explanations as will render it moderately intelligible to the general reader.

In the first place, it is desirable to remark that, for nearly a century, we followed Laplace's assumptions in regarding the planets as having been detached or thrown off from the sun, and the satellites as having been likewise thrown off from their several planets; and our problem was to find out how the postulated rings of vapor had condensed into the bodies now observed in the solar system. Thus with a fixed premise we were trying to find out how the planetary development had come about, and it scarcely occurred to any one that the premise itself might be false, and therefore all the efforts based on it in vain.

The turning point which enabled me to discover this error in the premises was a certain criterion based on the law of areas proposed by the distinguished French physicist Babinet, in 1861.[3] In this brief communication of three pages to the Paris Academy of Sciences, Babinet pointed out the contradiction of Laplace's cos-

[3] Cf. *Comptes Rendus*, March 18, 1861.

mogony resulting from the dynamical principle of the conservation of areas, and concluded that the classic nebular hypothesis was vitiated by a fallacy.

Like most negative critics, Babinet was beset by the weakness that he could tear down but could not build up. And as he substituted nothing for the theory of Laplace, the valuable criticism which he had made was scarcely noted by his contemporaries, and remained practically unknown to subsequent investigators. Thus we find in the writings of Lord Kelvin, Newcomb, Darwin, Tisserand and Poincaré no mention of the eminently useful criterion which Babinet had proposed in 1861; and it was allowed to slumber half a century in a forgotten number of the *Comptes Rendus*.

Looking back over this strange state of affairs, we naturally ask ourselves why Babinet did not proceed further with his investigations. To this question no certain answer can be returned, but it is probable that his inability to account for the remarkable roundness of the planetary orbits, which Laplace had explained by the process of gentle detachment, made him hesitate to go any further, and he gave up the effort in despair.

More than forty years ago the American astronomers Kirkwood and Pierce reached the conclusion that a mass so rare as the solar nebula must have been when it was expanded to fill the orbits of the planets, as imagined by Laplace, could not exert hydrostatic pressure so as to detach rings or zones of vapor; and they urged this objection as essentially fatal to the Laplacian theory. Here again the criticism was of the negative kind, like most of the criticism of Laplace's theory which appeared before and since their epoch; and it therefore shared the inherent weakness of all criticism which is not accompanied by work of constructive character. It does little good to break up our mental images if we cannot put better ones in their places; tearing down is easy, but building new structures much more difficult. And so long as the criticism was of purely negative character, it naturally failed to supersede Laplace's theory with a better one, and, by default, the ring theory has continued to hold its ground almost up to the present time.

It is not necessary to go into the details of more recent destruc-

tive criticism, except to say that no absolutely conclusive results were obtained until about two years ago, when I recognized from Babinet's criterion that we must unconditionally abandon the historical view that the planets have been detached from the sun and the satellites detached from their several planets. This led to the capture theory, which gives us the true conception of the origin of the solar system, and of other cosmical systems existing in space.

The earliest suggestion of the capture theory runs back a good many years, but it has not heretofore been accepted by professional astronomers familiar with celestial mechanics, because there was no recognized way in which the very circular orbits could be accounted for, except by the detachment theory of Laplace. It is only since the writer's discovery of the paramount part played by the resisting medium, some two years ago, that the capture theory has taken a form consistent with the established principles of dynamics.

As throwing light upon the earliest notice of the capture theory, we may quote a passage from Professor Barnard's article on "Jupiter's Fifth Satellite" in *Popular Astronomy,* for October, 1893, which I came across in making up the engravings for Volume II. of my "Researches" now in press. Barnard says:

> As was the case when Professor Hall discovered the satellites of Mars, many theories have been offered to account for the presence of the new body (Jupiter's fifth satellite). The asteroid zone between Mars and Jupiter is an endless source of material for such theories. It was suggested in 1877 that the Martian satellites were asteroids captured by Mars from the asteroid zone lying outside his orbit. These same theorizers have not failed to come up again and suggest that the fifth moon of Jupiter is a captured asteroid from the zone of asteroids lying inside the orbit of Jupiter. They never try to account for satellites of Saturn, Uranus and Neptune this way, because the asteroid mine is too far off; yet they are similar bodies, and undoubtedly had a similar origin. There is no question that this satellite has been there all along, and for infinite ages has been performing its revolutions about the planet, undetected until the night of 1892, September 9.

This account by Professor Barnard is exceedingly clear, and of great historical interest. It confirms the statement often made that the idea of capture was first entertained by amateurs. The doctrine has grown, however, from the theory of the capture of comets, which has been a subject of investigation by the most emi-

nent professional astronomers since the celebrated work of Laplace and Burkhardt, about 1805, on Lexell's comet of 1770. It is remarkable that in the course of the past century the capture theory of comets should have been highly developed by Leverrier, Adams, Schiaparelli, H. A. Newton, Callandreau, Tisserand and many others, while the capture of satellites should not have been seriously considered prior to the publication of the writer's "Dynamical Theory of the Capture of Satellites," in the *Astronomische Nachrichten,* Nos. 4341–42 (July, 1909).

The field of research opened up by the new theory is so large that it doubtless will be many years before it is exhausted; yet enough seems to have been done already to assure us that all the satellites are captured bodies. The result of this line of thought will be practically a new cosmogony. In order to render the results intelligible, we shall first outline the process of capture, and then recapitulate the conclusions at which we have arrived.[4]

(α) In the year 1836 the celebrated German mathematician Jacobi communicated to the Paris Academy of Sciences an integral of the differential equations of motion for the restricted problem of three bodies; the system being made up of a sun attended by a planet revolving about it in a circle, and a particle of insensible mass. Jacobi remarks that the integral may be applied to a body such as the terrestrial moon.

(β) In 1877 Dr. G. W. Hill developed and greatly perfected the theory of Jacobi's integral, and applied it to the lunar theory in a series of celebrated papers. Hill's work has since been the basis of the profound researches of Poincaré, Darwin and others on "Periodic Orbits" and related topics in celestial mechanics.

(γ) Dr. Hill showed that in the restricted problem of three bodies, implied in Jacobi's integral, there is a partition of the whole space into three parts—one about each of the large bodies, the sun and planet, and a larger domain enclosing both bodies—within which the power of control over the particle is vested in the two bodies individually and collectively, respectively. The closed surface about the earth includes the orbit of the moon, and the orbits of the other

[4] Cf. *A. N.*, 4341–42, 4343, and Publications A. S. P., No. 127, August, 1909.

satellites in like manner are within the closed surfaces about their several planets; and Dr. Hill remarks that this arrangement is necessary to secure stability. If a satellite is once within this region, with the surface of zero velocity closed about it, it cannot escape, but will always remain attached to the planet, and its radius vector will have a superior limit. How the moon and other satellites came within these closed regions Dr. Hill did not inquire; and subsequent investigators appear to have supposed that as these bodies cannot now escape from their planets, so also they cannot have come in from a remote distance, but must have originated where they now are. This is the view put forth by Moulton in his discussion of Professor W. H. Pickering's suggestion that Phœbe had been captured by Saturn; but such reasoning is easily shown to be erroneous by the following considerations:

(δ) Jacobi's integral, as originally given by him, is based on the differential equations for unrestricted motion in *empty space,* and no account is taken of the additional terms which must be added to the differential equations of the motion of the sun, planet and particle, when the motion is very slightly conditioned by the introduction of a nebular resisting medium, such as existed in the early history of our system, and is now observed to be widely diffused throughout nature. Jacobi's original integral, therefore, requires the addition of a secular term to represent the actual movement of a sun, planet and particle; and the complete expression for any particle whose coördinates are x_i, y_i, z_i becomes

$$x_i^2 + y_i^2 + \frac{2(1-\mu)}{\sqrt{(x_i - x_1)^2 + y_i^2 + z_i^2}} + \frac{2\mu}{\sqrt{(x_i - x_2)^2 + y_i^2 + z_i^2}} = C_i + a_i t_i. \qquad (1)$$

The secular term $a_i t_i$ makes the constant C_i increase with the time.

(ε) Now the surfaces of zero relative velocity, which define the closed spaces about the planets, have larger values of C the nearer we approach to the sun or planet. This is easily seen in the accompanying plate from Darwin's celebrated memoir on "Periodic Orbits." When the particle or satellite revolves against resistance, therefore, the second member of (1) increases, and there is a secu-

lar shrinkage of the surface of zero relative velocity. *Accordingly the particle drops down nearer and nearer these centers, and the surface finally becomes closed, leaving it no longer free to move about both bodies in the hour-glass shaped space, as formerly, but*

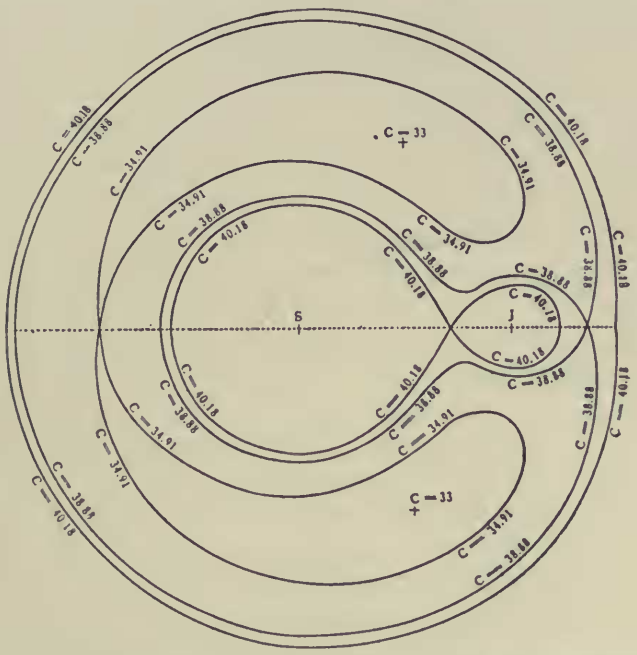

FIG. 1. Curves of Zero Velocity (Darwin). This diagram illustrates the hour-glass shaped space through which the particle may move and drop down nearer the sun or planet, till it becomes captured by one of the larger bodies.

restricted to the sphere of influence controlled by the sun or planet individually, as the case may be. The particle which once revolved about both the sun and planet can no longer do so, but becomes an inferior planet (satellite of the sun) or a satellite of the planet.

It is shown that the mean distance of the planet decreases as well as that of the satellite, but that the action of the resisting medium is relatively more effective on the satellite than on the planet in the inverse ratio of their radii, and therefore the planet approaches the sun very slowly and the satellite very rapidly. Accord-

ingly we may generally ignore the effect on the planet, and consider only the effect on the satellite. It is thus clear how the satellite drops down near these centers of attraction, and is finally captured by one of them.

(ζ) This is how all the satellites of the solar system were captured. At first they moved principally under the attraction of the sun, and could pass from the sun's to the planet's domain, through the neck of the hour-glass shaped space connecting the two spheres of influence. When the neck is narrow, Darwin says that a particle which passes from the sun's to the planet's control may revolve about it hundreds of times before quitting the planet's sphere to return again to the sun's control. And if resistance is meanwhile encountered, so that the neck of the surface of zero velocity becomes closed, it is clear that the particle never will quit the sphere of the planet's control, but will abide there permanently as a satellite.

(η) Thus it incontestably follows that the satellites of Jupiter, Saturn and other planets formerly moved about the sun, and since they were captured have had their orbits reduced in size and rounded up under the secular action of the resisting medium formerly pervading our solar system. *Satellites may cross over the line SJ before coming completely under the planet's control, in which case they will move retrograde.* In such cases the neck connecting the two spaces is extremely narrow. But as the neck usually is not so narrow as to produce crossing satellites, most of them naturally move direct, in accordance with observation. *This is the reason also why the planets have direct rotations on their axes. The planets have in no case been inverted, as some have recently supposed, in order to account for the retrograde motions of the outer satellites of Jupiter and Saturn.*

(θ) In the case of the terrestrial moon it is shown that the earth simply captured one of the twenty-seven million such planets which went to form the sun's immense mass. The moon came to us from the depths of space, and never was a part of the earth, as has long been supposed. Professor Sir G. H. Darwin's celebrated work of 1879 is shown to be based on chance coincidences, and not actual

physical history. All the details of the lunar terrestrial system are known to accord with the theory that the moon is a captured planet. (*a*) *It is shown by rigorous calculation from the theory of probability that the chances are infinity to one that the moon was captured like the other satellites.* (*b*) *It is likewise shown that the probability is infinity to one that the earth could not have rotated with sufficient rapidity to detach the moon.* As the theoretical possibility of the capture of the moon is beyond doubt, it is therefore certain that it actually occurred.

With this brief outline of the process of capture, we shall now sum up the conclusions at which we have arrived.

1. The planets never were detached from the sun by acceleration of rotation, as held by Laplace, but had their origin in the outskirts of the solar nebula, and have since neared the sun and had their orbits reduced in size and rounded up into almost perfect circles by moving for long ages against the resisting medium of nebulosity formerly pervading our system.

2. The view that the planets were formed at a great distance from the sun was advanced by the great Swiss mathematician Euler in 1749, before the theories of Kant (1755) and Laplace (1796) were promulgated; and he, too, based his conclusion on the secular effects of a resisting medium. Euler considered only the effect on the mean distance, but in 1805 Laplace showed by a more general investigation that the eccentricity also would be diminished; and it is this latter effect in producing the observed roundness of the orbits that gives us the principal clue to the true mode of formation of the solar system.

3. It therefore follows that the planets were developed in the solar nebula, but are in no sense of the word children of the sun; for they never were connected with the sun by any form of hydrostatic pressure and afterwards thrown off by acceleration of rotation, as has been generally believed.

(4) The satellites likewise never were mechanically connected with their several planets through any form of pressure and fluid equilibrium, but were originally independent planets, moving in regular elliptical orbits, and were afterwards captured and attached to

the planets about which they now revolve as satellites. Thus the satellites are in no sense of the word children of the planets and grandchildren of the sun, as we have been so long taught; but were formed in outer parts of the solar nebula, and simply survive out of a much vaster number of small bodies which have been swallowed up in laying the foundations of the sun and principal planets.

5. The best surviving illustration of the primordial condition of our system is afforded by the asteroids. The system was once quite filled with these satellites, and they revolved in orbits which were so eccentric that they crossed the paths of several of the planets. In time they have been largely absorbed in the sun and planets, and what remain have been thrown within the orbit of Jupiter, where they now revolve in comparative stability.

6. That our moon, likewise, was originally a planet which neared the earth and was finally captured and made a satellite. It was no part of the terrestrial globe detached by rapid rotation, as has been generally believed since the time of Anaxagoras, B. C. 500–428, and more recently taught by Laplace, Lord Kelvin, Sir George Darwin, Poincaré and other eminent writers.

7. The theories long current in geology and astronomy that the earth once rotated in two or three hours, so rapidly that it threw off a layer of peripheral matter now collected into the moon, are shown to be quite devoid of foundation. The effect of this advance will be to show that the globe never was highly oblate, and to correct the theories of geology, and greatly improve the science of astronomy.

8. The rotations of the planets on their axes have been produced by the capture and absorption of satellites. It is shown in the theory of the restricted problem of three bodies that most of the satellites should move direct, and it is by the capture and absorption of millions of these small masses that the planets have been given direct rotations on their axes.

9. The modification of the original obliquities of the planets is shown to depend on the capture and absorption of satellites. It is shown that in this way the obliquity of Jupiter was practically obliterated. If Saturn's mass were to be augmented till it became equal to that of Jupiter, his obliquity likewise would disappear.[5]

[5] Cf. *A. N.*, 4367.

The work of Stratton, implying planetary inversion, is shown to be inapplicable to the solar system, because based on a false premise.

10. As the satellites have all been captured, but were once independent planets, it will not seem strange that a few of them have retrograde motions; the capture theory explains this in a simple and easy manner, and it is in accord with the latest researches on the celebrated problem of three bodies, the treatment of which has been much improved by Jacobi, Hill, Poincaré, Darwin and other mathematicians.

11. As the planetary rotations are due to the capture and absorption of satellites, theory shows that the larger planets, as Jupiter and Saturn, ought to rotate most rapidly. This is in accordance with observation, and the nature of the cause at work shows that the earth never could have rotated much if any more rapidly than at present.

12. The cause of the secular acceleration of the moon's mean motion has been one of the leading problems of astronomy for over two centuries. In spite of all the researches of the greatest mathematicians, there remains an outstanding inequality of about 2″ which cannot be accounted for by gravitational or other definite theory. This anomaly is now explained by the fact that the moon is a captured planet, and therefore slowly nearing the earth, owing to the action of a resisting medium, in the nature of cosmical dust pervading the regions where the planets move.

13. The roundness of the orbits of the planets and satellites has been remarked from the earliest ages of science, and this phenomenon, which led Plato, Aristotle and other Greek sages to declare that the heavenly motions are perfect because they are circular, is now shown to be due to the secular action of a resisting medium which has reduced the size of the planetary orbits and well-nigh obliterated their eccentricities; and not at all to these bodies having been detached by rotation and set revolving in orbits which were originally nearly circular, as incorrectly held by Laplace.

14. Around each planet there circulates a vortex of cosmical dust, of which the satellites alone are large enough and bright enough to be visible in our telescopes. The descent of this material

against the surfaces of the sun and planets gives rise to the observed but heretofore perplexing accelerations of the equatorial regions of these globes.

15. The descent of matter upon the sun increases its mass and gives rise to a small secular acceleration of the earth amounting to about 0″.75 per century, which, as Mr. Cowell has shown, is also indicated by the observations of the eclipses during the past 3,000 years.

16. And just as the earth never rotated very rapidly, and has not been appreciably retarded by the effects of tidal friction, so also Venus likewise has escaped a corresponding retardation of axial rotation, and still rotates in 23 hours 21 minutes, as has been held by observers since the days of Cassini, 1667. Accordingly it follows that the conditions of this planet are more like those of the earth than any other body of our system. Mars rotates 41 minutes slower than the earth, while Venus rotates 35 minutes faster; and as the former planet is about as much outside of the earth's orbit as the latter is inside, there is seen to be a profound physical cause which has operated to establish the period of 23 hours 21 minutes first inferred from observations taken over two centuries ago. The planet Venus, therefore, is habitable and probably inhabited by some kind of intelligent beings.

17. The moon was once an independent planet, and when revolving in the region of the asteroids, suffered numerous collisions with satellites; this is the cause of the immense, round, sunken craters which have puzzled astronomers since the time of Galileo. The traditional theory that they are volcanic is quite devoid of foundation, and now definitely and finally disproved.

18. The solar system extends much beyond Neptune, and several of the unseen planets revolving near the outskirts of the system may yet be discovered by observation. Neptune's orbit is too round to be the last of the planets, because this roundness indicates that the nebulous medium was quite dense at that distance, and consequently that the limits of the system are much further out.

19. It has long been known that the periodic comets are captured bodies which have suffered transformation of their orbits

under the action of the planets. The theory is now extended to the asteroids and satellites, and these two classes of bodies are shown to be closely related. The survival of satellites near the principal planets shows that our system was once filled with these small masses. Such moons naturally developed in the condensation of a nebula, and all nebulæ include multitudes of solid globes in addition to the gaseous matter shown by the spectroscope.

20. The collisions of satellites with the larger globes, as shown by the battered surface of our moon, give rise to part of the light of the nebulæ, and no doubt also to some of the cosmical dust with which they are filled.

21. The whirling of a spiral nebula is due to the unsymmetrical meeting of two streams of nebulosity, which thus coil up, and settle down under the effects of mutual gravitation; or to the mere gravitational settling of a nebula of unsymmetrical figure. The inevitable result is a whirling cosmical vortex, and eventually a star surrounded by a cosmical system.

22. Nearly all single stars have planetary system revolving about them, and in the immensity of the starry heavens an infinite number of the planets are habitable, and no doubt actually inhabited. Life is almost as general a phenomenon in the universe as matter itself, though our dominant materialistic philosophy is loth to admit it.

23. We can see only visual and spectroscopic binary stars in the sidereal universe, owing to the immense distances which render the smaller bodies wholly invisible in our telescopes; but we know, from the example of the solar system and from the causes which have operated in its formation, that planets and satellites exist everywhere about the fixed stars.

24. In star clusters the motion is shown to be of a spiral character, as in the nebulæ, where we can trace the streams of movement by the nebulosity, and the same theory is applied to the milky way. It is shown by calculation based on the best modern data, that the extent of the sidereal universe actually exceeds the vast dimensions found by Sir William Herschel, and of late years held to be extreme.

It will readily be understood that the lines of argument by

which these results are established are of mathematical character, and in accordance with the principles of dynamics. It is shown, for example, that the spirals observed among the nebulæ are *chance spirals,* and not true geometrical figures. And the general theory is established that the nebulæ are formed by the falling together of cosmical dust expelled from the stars by the radiation-pressure of their light and by electric forces. When this fine dust is precipitated under the action of cathode rays it forms meteorites, and the collection of meteorites forms satellites and larger cosmical bodies.

A nebula is a cloud of cosmical dust with moons and planets intermixed. The falling together of such nebulosity necessarily produces cosmical vortices, and these are the whirlpool nebulæ so long observed in the heavens but not heretofore understood. The expulsion of fine dust from the more active stars gives the primordial material for the formation of nebulæ; the condensation of the nebulæ in turn forms stars, so that the total process is a cyclical one, involving both the aggregation of matter into stellar centers and its subsequent diffusion to form new nebulæ, stars and systems.

As the second volume of my "Researches on the Evolution of the Stellar Systems" is a work of nearly 750 pages, it will readily be understood that this summary is too brief to give more than a faint outline of the work. Yet as the results are of general interest to a large class of readers, I have thought they might be mentioned in this brief review.

Our age is a peculiar one, in that with the progress of astronomy vast masses of observational data are accumulated by the persevering industry of self-denying men of science; but so long as these data cannot be put together to yield us the long-sought laws of cosmical evolution, the outcome is almost as vain as the weaving of Penelope's web. Natural philosophers believe, however, that the time is now auspicious for a great advance, not merely in the details, but also in the laws and principles of exact astronomical science. One of the ultimate aims of the physical sciences in all ages has been the discovery of the laws of cosmical evolution.

If with the modern improvements in the mathematical treatment of the problem of three bodies, and the observational data derived from photographic study of the nebulæ and clusters, as well as from the visual and spectroscopic binary stars, this progress be not possible in our time, it is difficult to see how better results can be expected in the future.

I have therefore labored with no ordinary energy to weave together the scattered and discordant threads of argument regarding phenomena which heretofore could not be brought into harmonious relationship. And I have been fortunate enough to attain an unexpected degree of success; so that I cannot doubt that the result will go far towards a permanent solution of the problems of cosmical evolution, which is certainly an urgent *desideratum* of our time.

U. S. Naval Observatory,
Mare Island, California,
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